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Biosolids application to no-till dryland agroecosystems

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ABSTRACT

Dryland agroecosystems are generally ideal environments for recycling biosolids. However, what is the efficacy of biosolids addition to a no-till dryland management agroecosystem? From 2000 to 2010, we studied application of biosolids from the Littleton/Englewood, CO Wastewater Treatment Plant versus commercial N fertilizer in dryland no-till wheat (*Triticum aestivum*, L.)–fallow (WF) and wheat–corn (*Zea mays*, L.)–fallow (WCF) rotations at a site approximately 40 km east of Byers, CO. We tested if biosolids would produce the same yields and grain P, Zn, and Ba concentrations as an equivalent rate of N fertilizer, that biosolids-borne P, Zn, and Ba would not migrate below the 10 cm soil depth, and that biosolids application would result in the same quantity of residual NO_3–N as the equivalent N fertilizer rate. Biosolids and N fertilizer produced similar wheat and corn yields; but, biosolids application resulted in smaller wheat grain Ba due to the soil formation of $BaSO_4$. Biosolids application produced greater NO_3–N concentrations than N fertilizer in the 30–60 and 60–90 cm depths for the WF rotation and all but the 5–10 and 120–150 cm depths for the WCF rotation. We concluded that biosolids application in a no-till managed dryland agroecosystem is an efficacious method of recycling this nutrient source.

1. Introduction

Recycling of biosolids on dryland wheat can supply organic material and a slow-release source of N (Barbarick et al., 1992). Barbarick and Ippolito (2000, 2007) found that continuous application of biosolids from the Littleton/Englewood, CO wastewater treatment plant to dryland wheat provides 8 kg N Mg^{-1}. Castillo et al. (2011) found that incorporating biosolids in elephantgrass (*Pennisetum purpureum* Schum.) production resulted in a 25% increase in total organic N mineralization over surface application. Barbarick et al. (1998) also found that biosolids application significantly increased ammonium bicarbonate-diethylaminepentaacetic acid (AB-DTPA) extractable Zn to the 60–100-cm depth after six biosolids additions. In 2003, the USEPA added Ba to the "candidate pollutants for exposure and hazard screening" (USEPA, 2003). Yet, Ippolito and Barbarick (2006) found biosolids additions actually lowered Ba plant availability. All of these studies involved tilling the biosolids into the top 20 cm of soil. A new question related to soil management in a biosolids beneficial-use program is: How does biosolids application affect N, P, Zn, and Ba dynamics in a no-till dryland agroecosystem?

The standard rotation for dryland agroecosystems in the western Great Plains has been wheat–fallow (WF). To make more optimal use of soil–water storage and precipitation, more intensive rotations like wheat–corn–fallow (WCF) have gained in popularity (Peterson et al., 1993; Peterson and Westfall, 2004; Nielsen et al., 2010).

Little information exists on no-till management of biosolids amended dryland agroecosystems; however, information from research on land application to pastures or rangelands provide clues on the potential effects of surface application without incorporation. Joshua et al. (1998) discuss surface biosolids additions to sheep pastures in Australia and Pierce et al. (1998) report the effects of surface application in a semi-arid shrubland. Both studies showed that applications up to 30 Mg ha^{-1} can beneficially affect forage production. Fresquez et al. (1990) found that the most favorable soil fertility on a Litle silty clay loam (Mollic Camborthids) and largest blue grama (*Bouteloua gracilis* (H.B.K.) Lag.) growth occurred with biosolids rates of 22.4 or 45 Mg ha^{-1}. Using sequential extraction on an Altvan sandy loam (Aridic Argiustolls) from a shortgrass steppe rangeland dominated by blue grama and western wheatgrass (*Pascopyrum smithii*, (Rydb.) A. Love), Ippolito and Barbarick (2009) established that biosolids-borne Cu moved into the 8–15 and 15–30 cm depths following single or repeated applications of up to 30 Mg biosolids ha^{-1} while biosolids-borne Zn did not move significantly.

Our objective was to compare agronomic rates of biosolids to an equivalent rate of N fertilizer in conjunction with WF and WCF crop rotations. Our hypotheses were that biosolids addition compared to N fertilizer:

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Table 1
Growing season precipitation for the biosolids–dryland agroecosystem site near Byers, CO, 2000–2010 (Weather station was installed in April, 2000).

Year	Wheat vegetative September–March	Wheat reproductive April–June	Corn preplant July–April	Corn growing season May–October	Corn critical July 16–August 26[a]
			cm precipitation		
2000–1	8.4	16.0	24.1	24.4	5.9
2001–2	5.3	5.6	15.5	9.9	2.2
2002–3	2.8	8.4	8.6	23.4	1.7
2003–4	0.8	5.8	7.6	21.8	4.7
2004–5	4.3	10.9	13.5	21.8	8.8
2005–6	6.4	3.3	16.3	20.1	4.7
2006–7	8.9	9.4	22.4	20.8	13.5
2007–8	3.8	5.6	18.3	26.7	18.3
2008–9	5.3	21.1	30.0	32.8	7.9
2009–10	8.3	13.9	25.9	17.7	5.2

[a] Nielsen et al. (2010).

1. Will produce similar wheat and corn yields ($P > 0.05$).
2. Will produce comparable grain concentrations of P, Zn, and Ba ($P > 0.05$). Since biosolids adds excess P when applied at the N agronomic rate (Shober and Sims, 2003), we monitored grain P concentrations. We studied grain Zn since soils in the western Great Plains typically contain less than adequate soil levels (Follett and Westfall, 2004).
3. Will not differ in plant-available soil concentrations (AB-DTPA extractable; Barbarick and Workman, 1987) of P, Zn, and Ba below 10 cm ($P > 0.05$). This hypothesis indicates that these elements will not migrate below 10 cm.
4. Will not differ in soil accumulation of nitrate–N (NO_3–N) through a depth of 180 cm ($P > 0.05$). This hypothesis assumes that we were able to match the crop N requirements with the N availability supplied by the biosolids or the N fertilizer.

2. Materials and methods

We established our research on land owned by the Cities of Littleton and Englewood (L/E) in eastern Adams County, approximately 40 miles east of Byers, CO. The latitude longitude for the plot corners are 39°45′47″/103°47″50″ (southwest), 39°45′47″/103°47″17″ (southeast), 39°46′7″/103°47″50″ (northwest), 39°46′7″/103°47″17″ (northeast). A tenant farming family manages the site. Soils belong to the Adena–Colby association where the Adena soil is classified as an Ustollic Paleargid and Colby is classified as an Ustic Torriorthent. No-till management was used in conjunction with crop rotations of WF, WCF, and corn–fallow–wheat (CFW); the only soil disturbance that occurred was with the wheat and corn planting equipment. We installed a Campbell Scientific® weather station at the site in April 2000. Precipitation for the 2000 through 2010 growing seasons, and for the critical grain filling periods, are presented in Table 1.

We designed the experiment so that every phase of each rotation was present during each year. The rotational phases present each year were W–F, F–W, W–C–F, C–F–W, and F–W–C (5 total plots per replication) in a randomized complete block design in a split-plot arrangement with two replications. Each plot was 30 m wide by approximately 800 m long. Available contiguous land area limited us to two replications. Each whole plot was split so that one 15-m section received commercial N fertilizer (34-0-0) and the second 15-m section received biosolids (applied by L/E with a manure spreader). The experiment was initiated in fall 1999 when the biosolids treatments were first applied. We randomly selected which strip in each rotation received N fertilizer or biosolids. Biosolids were applied in August on wheat plots and in March on corn plots. Based on research by Barbarick and Ippolito (2000, 2007), we assumed each Mg of dry biosolids would provide 8 kg available N for each application. Table 2 provides the characteristics of the L/E biosolids. The N fertilizer and biosolids applications

Table 2
Littleton/Englewood biosolids composition used at the Byers research site, 1999–2005.

Parameter	1999 Wheat	2000 Corn	2001 Corn	2001 Wheat	2003 Corn	2003 Wheat	2004 Wheat	2005 Corn	Avg.	Range
Solids, g kg^{-1}	217	–	210	220	254	192	197	211	214	192–254
pH	7.6	7.8	8.4	8.1	8.5	8.2	8.8	8.2	8.2	7.6–8.8
EC, dS m^{-1}	6.2	11.2	10.6	8.7	7.6	7.4	4.5	5.1	7.7	4.5–11.2
Org. N, g kg^{-1}	50	47	58	39	54	46	43	38	47	38–58
NH_4–N, g kg^{-1}	12	7	14	16	9	13	14	14	12	7–16
NO_3–N, g kg^{-1}	0.023	0.068	0.020	0.021	0.027	0.016	0.010	0	0.023	0–0.068
K, g kg^{-1}	5.1	2.6	1.6	1.9	2.2	2.6	2.1	1.7	2.5	1.6–5.1
P, g kg^{-1}	29	18	34	32	26	28	29	13	26	13–34
Al, g kg^{-1}	28	18	15	18	14	15	17	10	17	10–28
Fe, g kg^{-1}	31	22	34	33	23	24	20	20	26	20–34
Cu, mg kg^{-1}	560	820	650	750	596	689	696	611	672	560–820
Zn, mg kg^{-1}	410	543	710	770	506	629	676	716	620	410–770
Ni, mg kg^{-1}	22	6	11	9	11	12	16	4	11	4–22
Mo, mg kg^{-1}	19	22	36	17	21	34	21	13	23	13–36
Cd, mg kg^{-1}	6.2	2.6	1.6	1.5	1.5	2.2	4.2	2.0	2.7	1.5–6.2
Cr, mg kg^{-1}	44	17	17	13	9	14	18	14	18	9–44
Pb, mg kg^{-1}	43	17	16	18	15	21	26	16	22	15–43
As, mg kg^{-1}	5.5	2.6	1.4	3.8	1.4	1.6	0.5	0.05	2.1	0.05–5.5
Se, mg kg^{-1}	20	16	7	6	17	1	3	0.07	8.8	0.07–20
Hg, mg kg^{-1}	3.4	0.5	2.6	2.0	1.1	0.4	0.9	0.1	1.4	0.1–3.4
Ag, mg kg^{-1}	–[a]	–	–	–	15	7	0.5	1.2	5.9	0.5–15
Ba, mg kg^{-1}	–	–	–	–	–	–	533	7	270	7–533
Be, mg kg^{-1}	–	–	–	–	–	–	0.05	<0.001	0.05	<0.05
Mn, mg kg^{-1}	–	–	–	–	–	–	239	199	219	199–239

[a] – Indicate analyses were not completed.

Table 3
Biosolids and N fertilizer applications for various dryland rotations at the Byers research site, 1999–2005.

Year	Rotation	Plot number	Biosolids rate, Mg ha^{-1}	N fertilizer rate, kg ha^{-1}
1999–2000	Wheat–Fallow	103, 201	5.4	43
	Wheat–Corn–Fallow	107, 210	5.4	43
	Corn–Fallow–Wheat	108, 202	9.0	72
2000–2001	Wheat–Fallow	106, 208	0	0
	Wheat–Corn–Fallow	102, 203	0	0
	Corn–Fallow–Wheat	107, 210	12.3	99
2001–2002	Wheat–Fallow	103, 201	4.5	36
	Wheat–Corn–Fallow	108, 202	4.5	36
	Corn–Fallow–Wheat	102, 203	12.5	100
2002–2003	Wheat–Fallow	106, 208	4.5	36
	Wheat–Corn–Fallow	107, 210	4.5	36
	Corn–Fallow–Wheat	108, 202	0	0
2003–2004	Wheat–Fallow	103, 201	4.5	36
	Wheat–Corn–Fallow	102, 203	4.5	36
	Corn–Fallow–Wheat	107, 210	0	0
2004–2005	Wheat–Fallow	106, 208	6.7	54
	Wheat–Corn–Fallow	108, 202	6.7	54
	Corn–Fallow–Wheat	102, 203	9.0	72
Total by plots	Wheat Fallow	103, 201	14.4	115
	Wheat Fallow	106, 208	11.2	90
	Wheat Corn Fallow and Corn Fallow Wheat	107, 210	22.2	178
	Wheat Corn Fallow and Corn Fallow Wheat	108, 202	20.2	162
	Wheat Corn Fallow and Corn Fallow Wheat	102, 203	26.0	208

were based on soil test recommendations determined for each plot for each crop. The last biosolids and N fertilizer application was for corn in the spring of 2005 due to accumulation of NO_3–N to the extent that N additions would not be recommended (Davis and Westfall, 2009). Biosolids and N fertilizer application rates for 1999 through 2005 are given in Table 3.

We completed wheat harvests in July 2000 through 2010, except 2006, and corn harvests in October, except 2002 through 2006. We experienced a wheat-crop failure in 2006 and corn-crop failures in 2002 through 2006. For each harvest, the grain was cut from four areas of 1.5 m by approximately 30 m. We determined the yield for each area and then took a subsample from each cutting for subsequent elemental grain analyses for P, Zn, and Ba concentrations (Ippolito and Barbarick, 2000).

Following each harvest, composite soil samples were collected using a Giddings® hydraulic probe. For AB-DTPA extractable P,

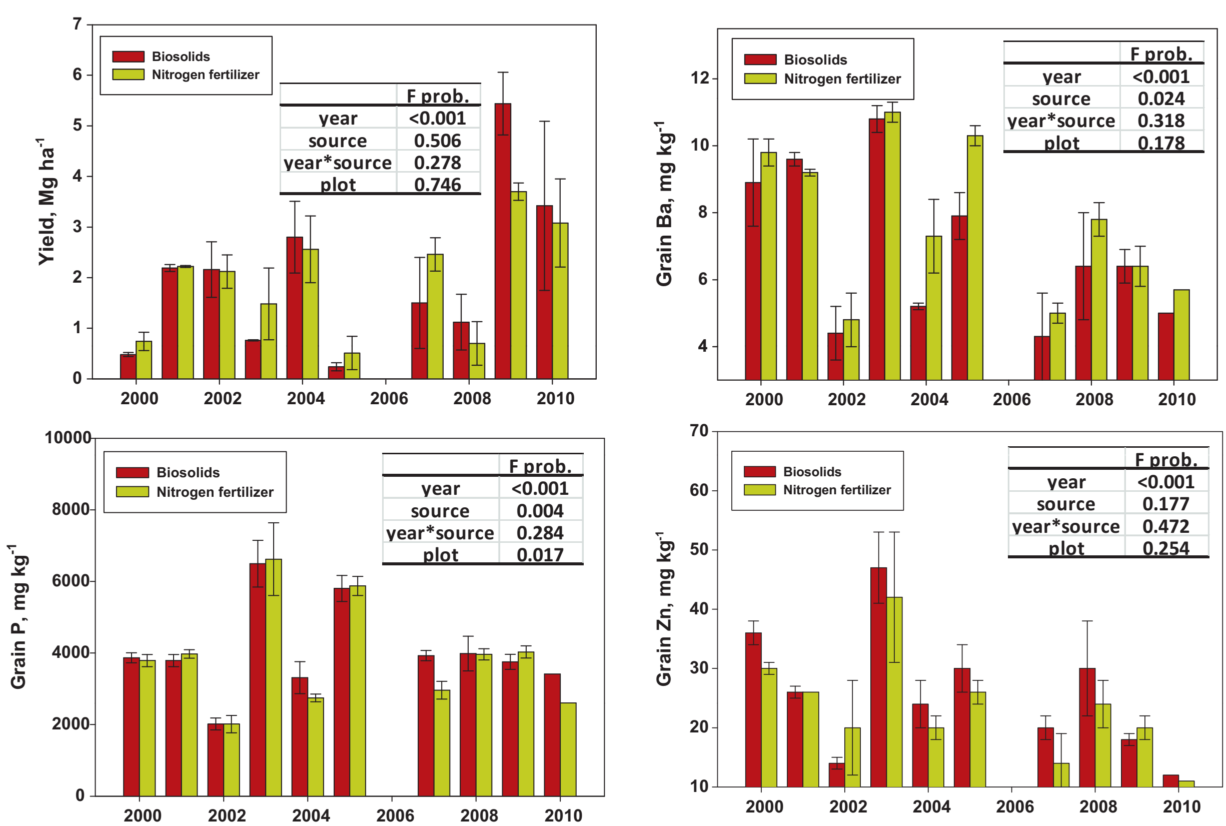
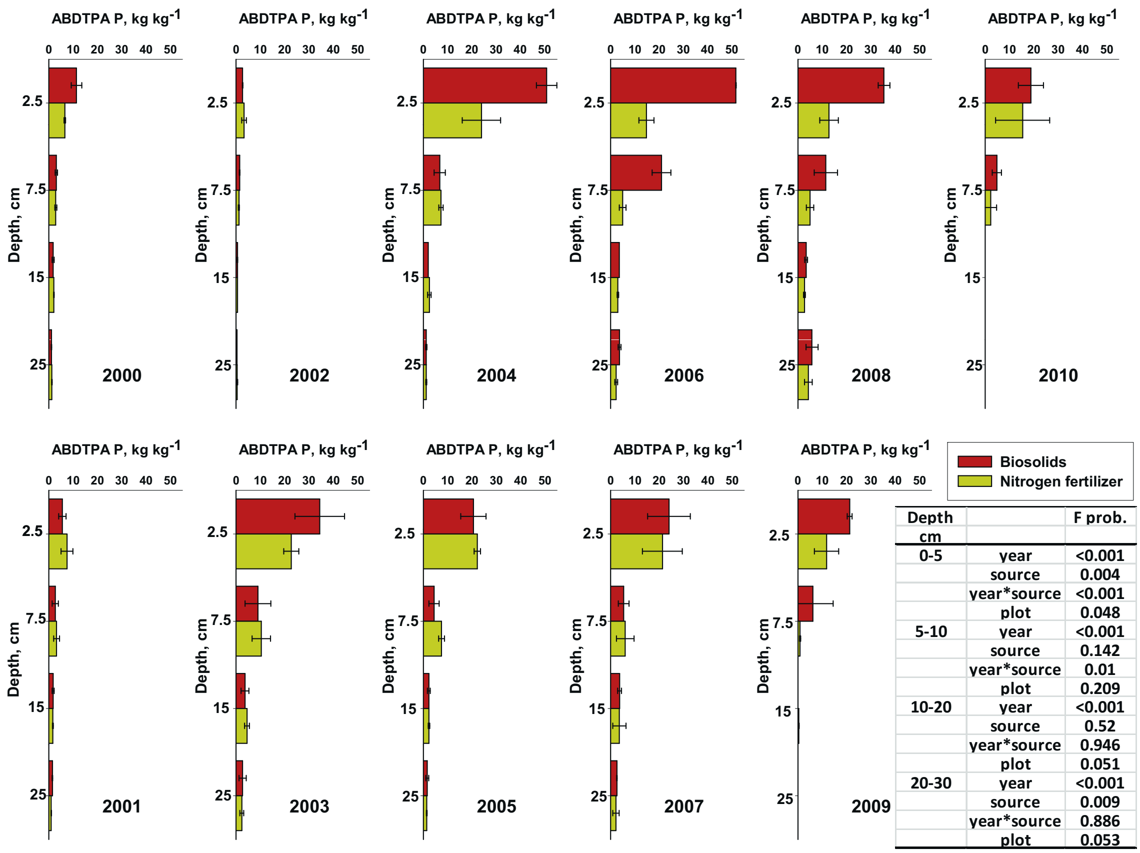
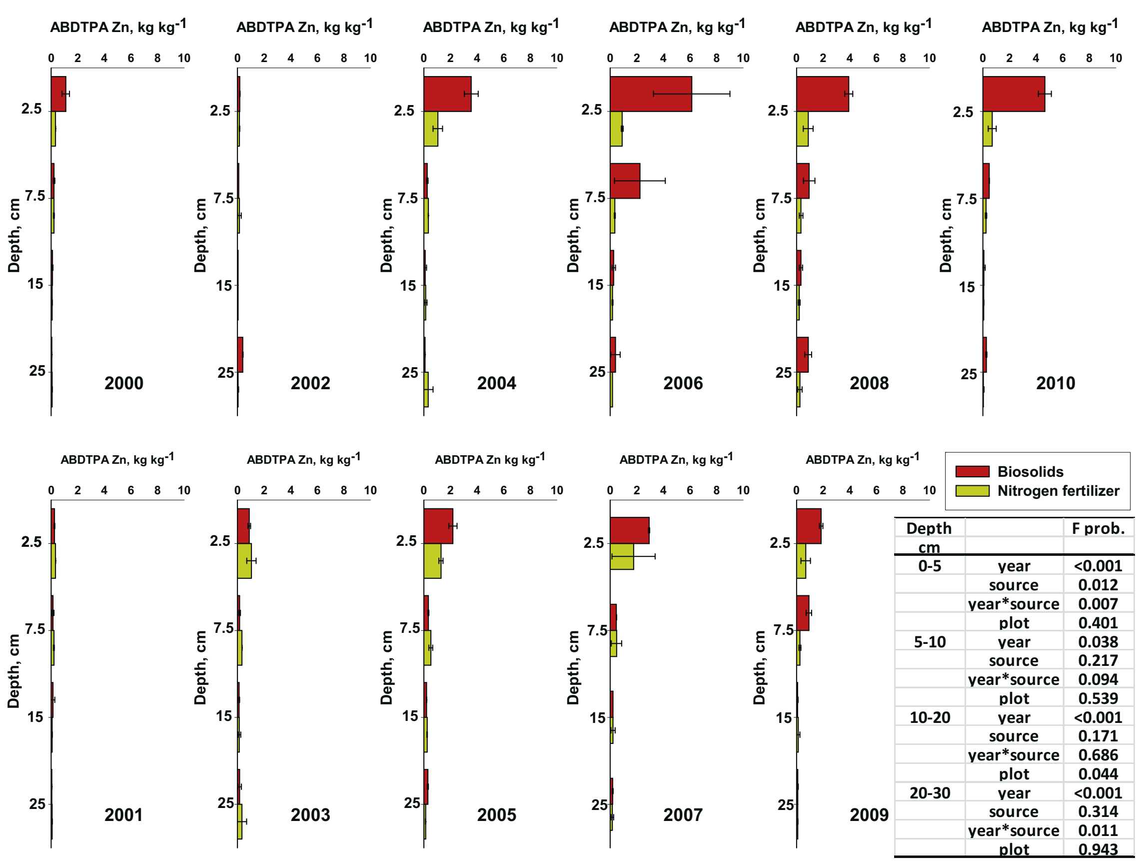


Fig. 1. Wheat yields and grain P, Zn, and Ba for the wheat–fallow rotation at the Byers, CO location, 2000–2010. Error bars depict the standard error of the mean.



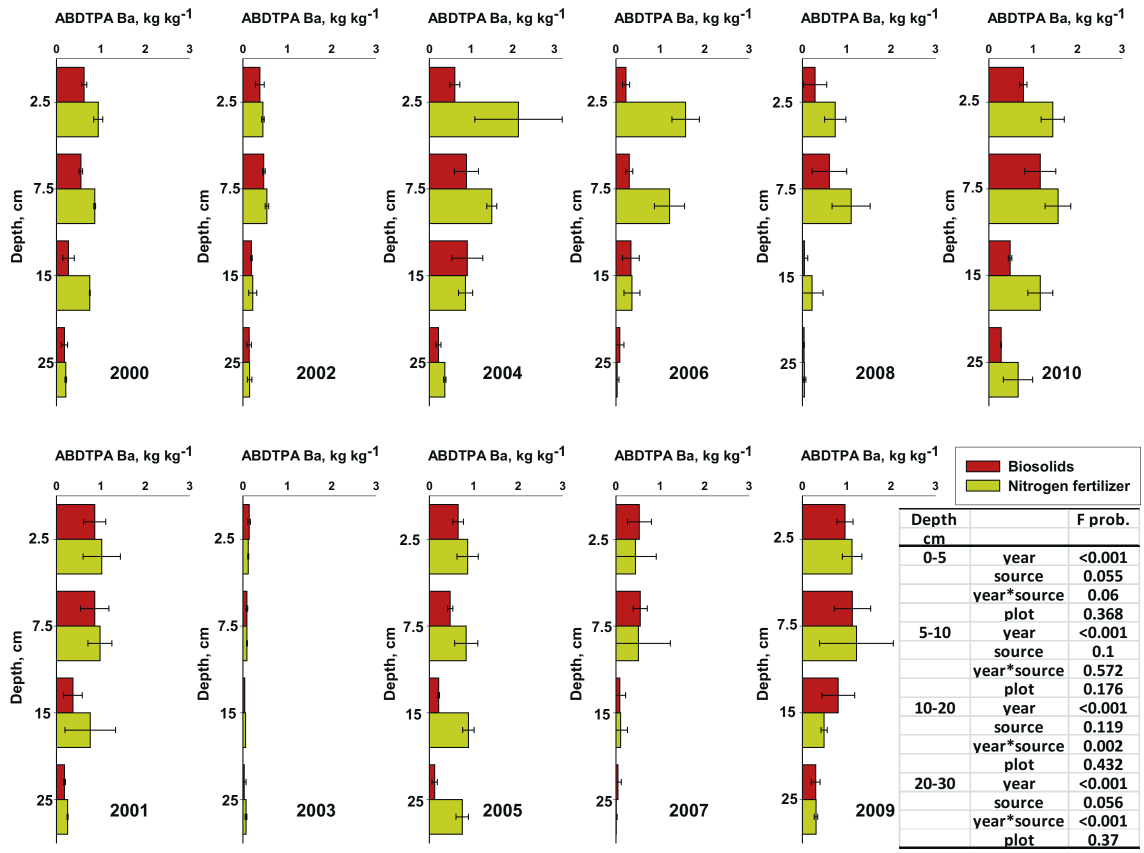
Depth cm		F prob.
0-5	year	<0.001
	source	0.004
	year*source	<0.001
	plot	0.048
5-10	year	<0.001
	source	0.142
	year*source	0.01
	plot	0.209
10-20	year	<0.001
	source	0.52
	year*source	0.946
	plot	0.051
20-30	year	<0.001
	source	0.009
	year*source	0.886
	plot	0.053

Fig. 2. AB-DTPA P for the wheat–fallow rotation at the Byers, CO location, 2000–2010. Error bars depict the standard error of the mean.



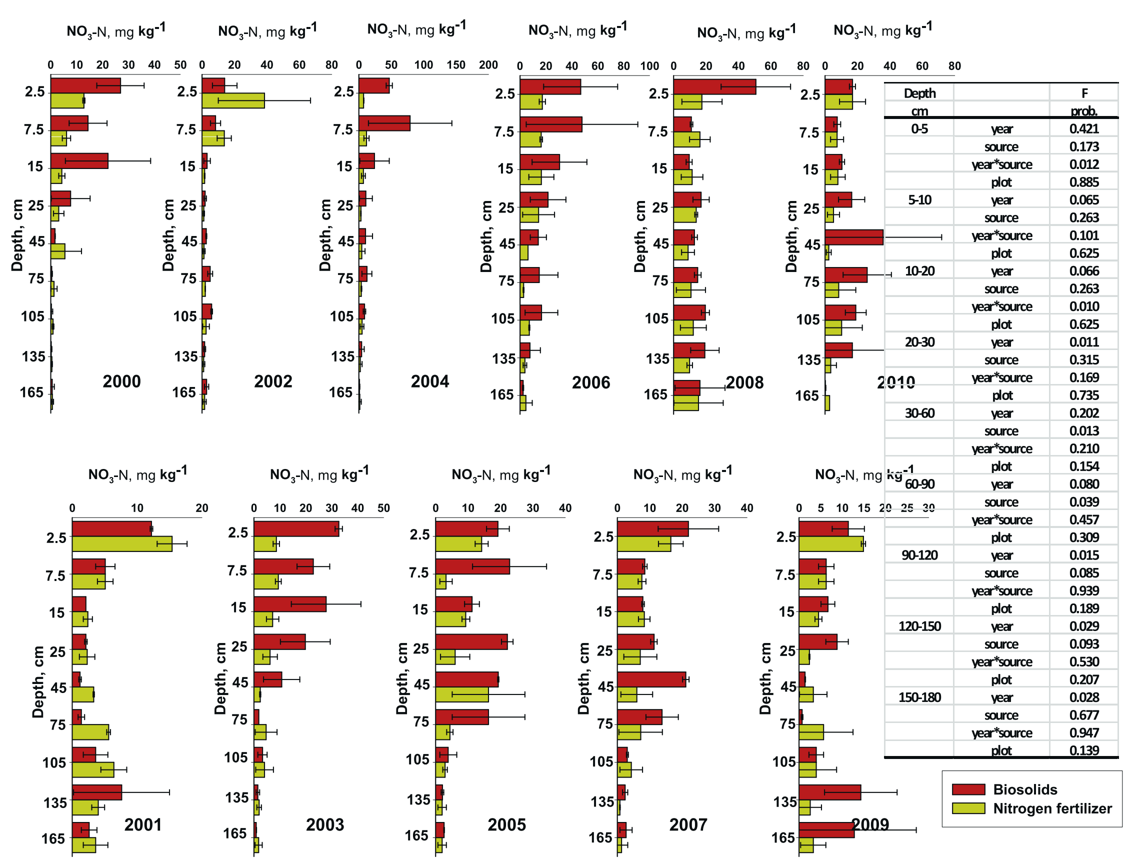
Depth cm		F prob.
0-5	year	<0.001
	source	0.012
	year*source	0.007
	plot	0.401
5-10	year	0.038
	source	0.217
	year*source	0.094
	plot	0.539
10-20	year	<0.001
	source	0.171
	year*source	0.686
	plot	0.044
20-30	year	<0.001
	source	0.314
	year*source	0.011
	plot	0.943

Fig. 3. AB-DTPA Zn for the wheat–fallow rotation at the Byers, CO location, 2000–2010. Error bars depict the standard error of the mean. Error bars depict the standard error of the mean.



Depth cm		F prob.
0-5	year	<0.001
	source	0.055
	year*source	0.06
	plot	0.368
5-10	year	<0.001
	source	0.1
	year*source	0.572
	plot	0.176
10-20	year	<0.001
	source	0.119
	year*source	0.002
	plot	0.432
20-30	year	<0.001
	source	0.056
	year*source	<0.001
	plot	0.37

Fig. 4. AB-DTPA Ba for the wheat–fallow rotation at the Byers, CO location, 2000–2010. Error bars depict the standard error of the mean.



Depth cm		F prob.
0-5	year	0.421
	source	0.173
	year*source	0.012
	plot	0.885
5-10	year	0.065
	source	0.263
	year*source	0.101
	plot	0.625
10-20	year	0.066
	source	0.263
	year*source	0.010
	plot	0.625
20-30	year	0.011
	source	0.315
	year*source	0.169
	plot	0.735
30-60	year	0.202
	source	0.013
	year*source	0.210
	plot	0.154
60-90	year	0.080
	source	0.039
	year*source	0.457
	plot	0.309
90-120	year	0.015
	source	0.085
	year*source	0.939
	plot	0.189
120-150	year	0.029
	source	0.093
	year*source	0.530
	plot	0.207
150-180	year	0.028
	source	0.677
	year*source	0.947
	plot	0.139

Fig. 5. Soil NO_3–N for the wheat–fallow rotation at the Byers, CO location, 2000–2010. Error bars depict the standard error of the mean.

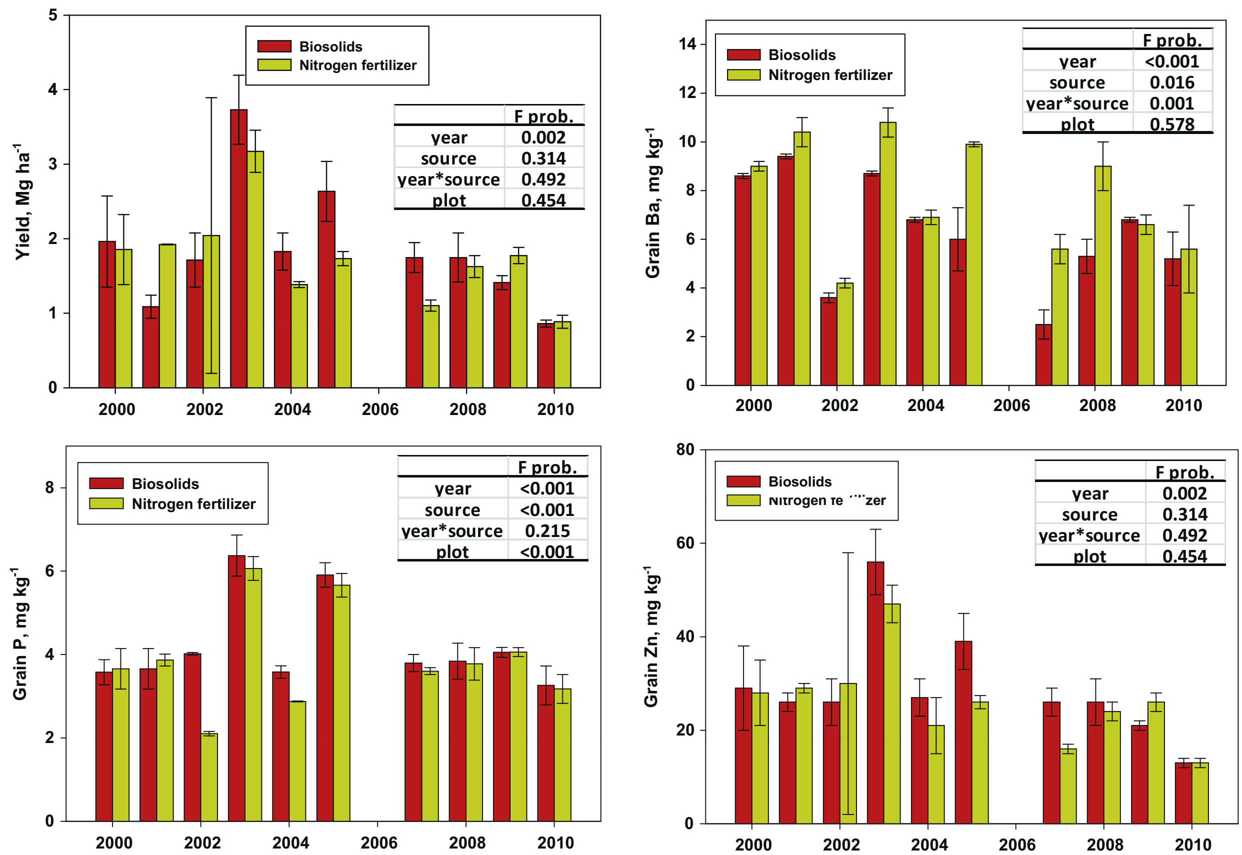


Fig. 6. Wheat yields and grain P, Zn, and Ba for the wheat–corn–fallow rotation at the Byers, CO location, 2000–2010. Error bars depict the standard error of the mean.

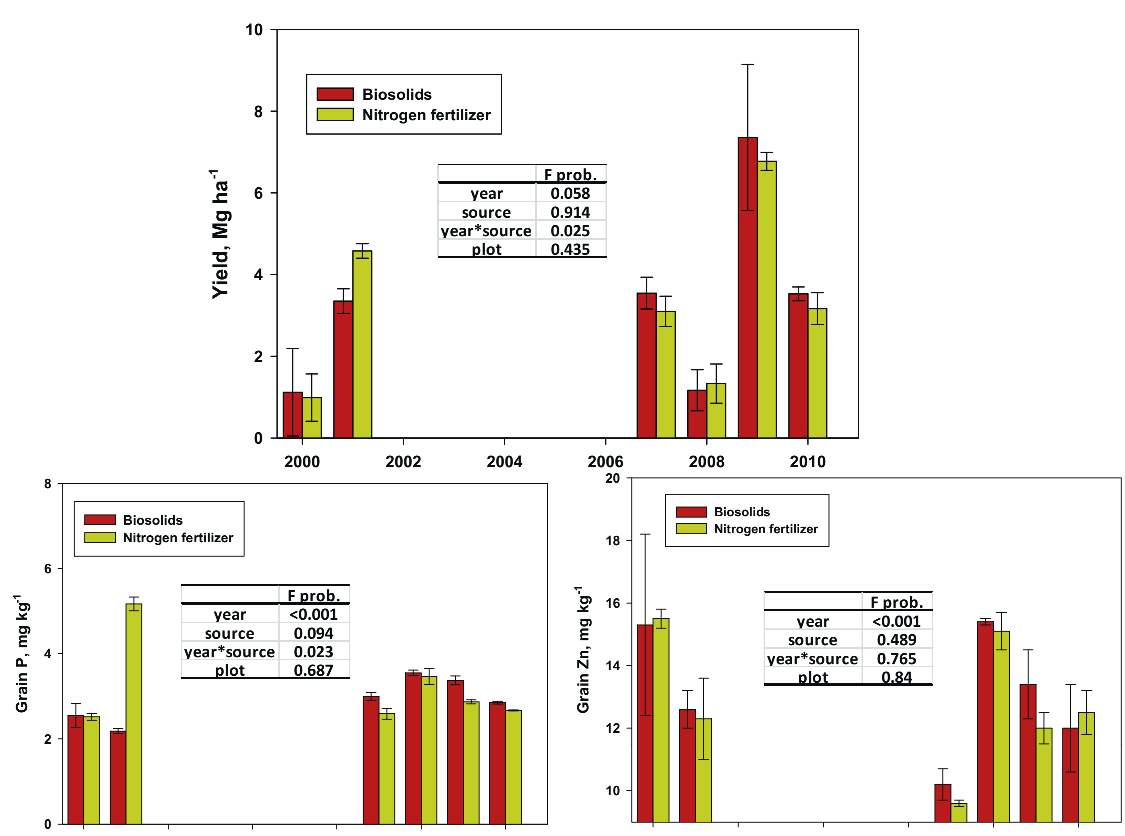
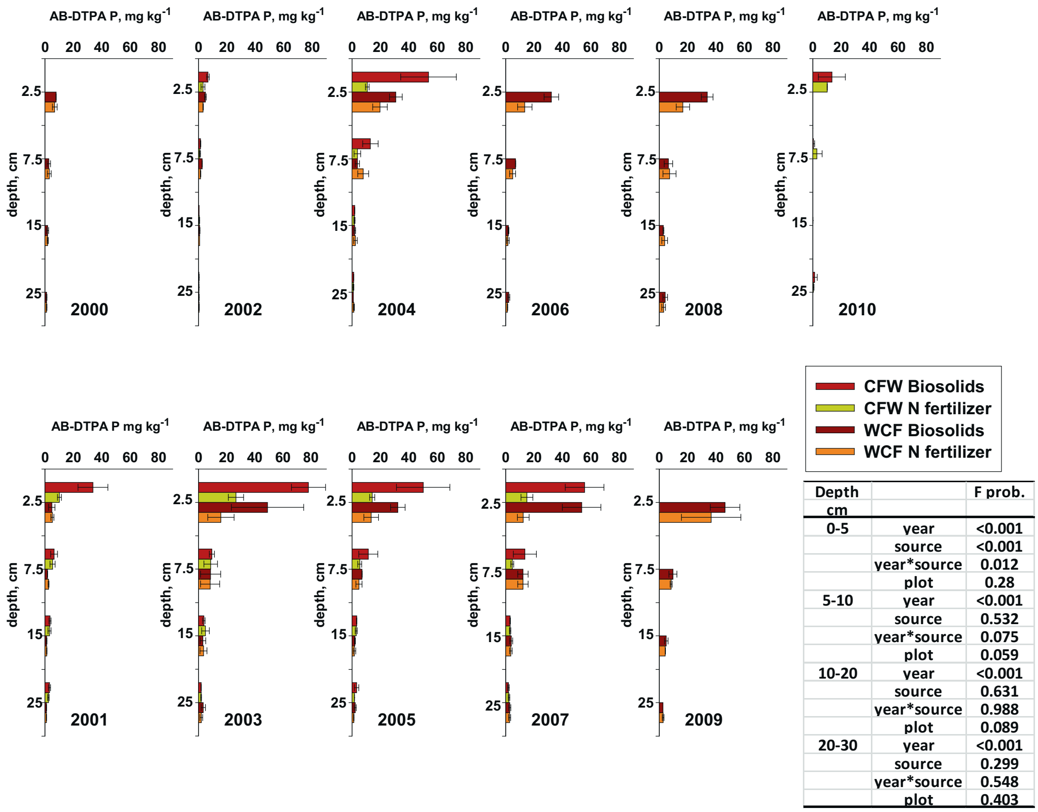
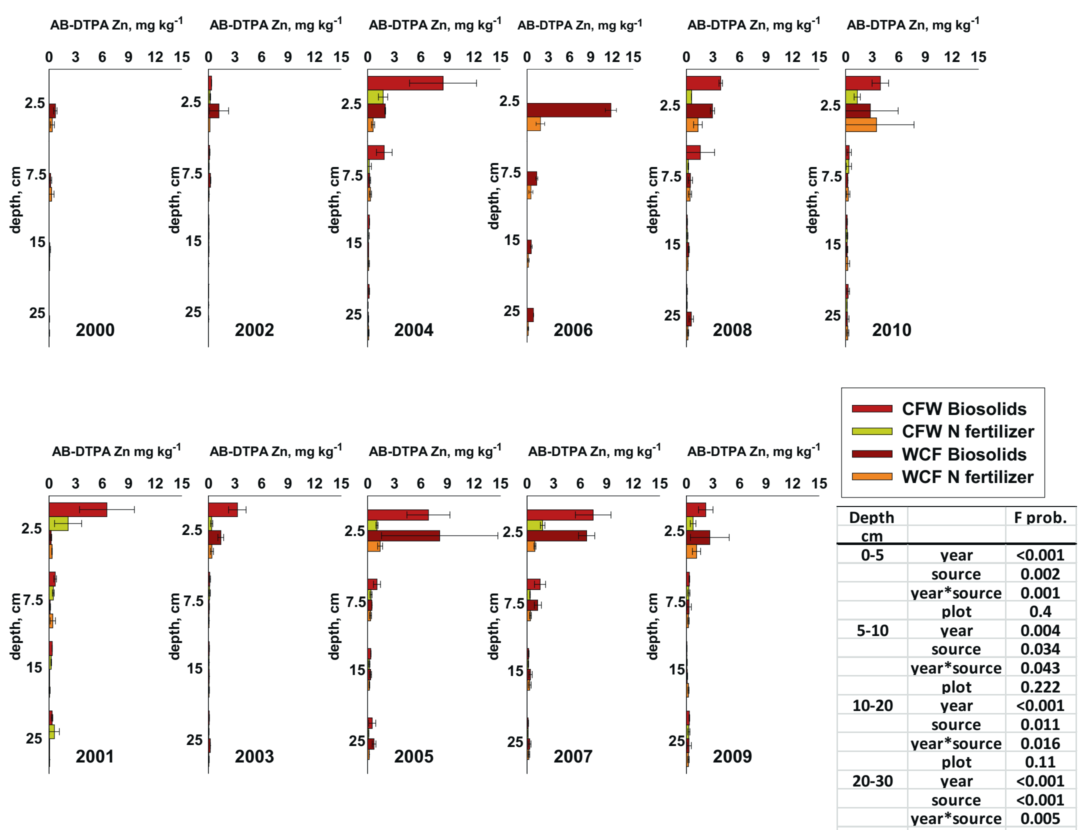


Fig. 7. Corn yields and grain P, Zn, and Ba for the corn–fallow–wheat rotations at the Byers, CO location, 2000–2010. Error bars depict the standard error of the mean.



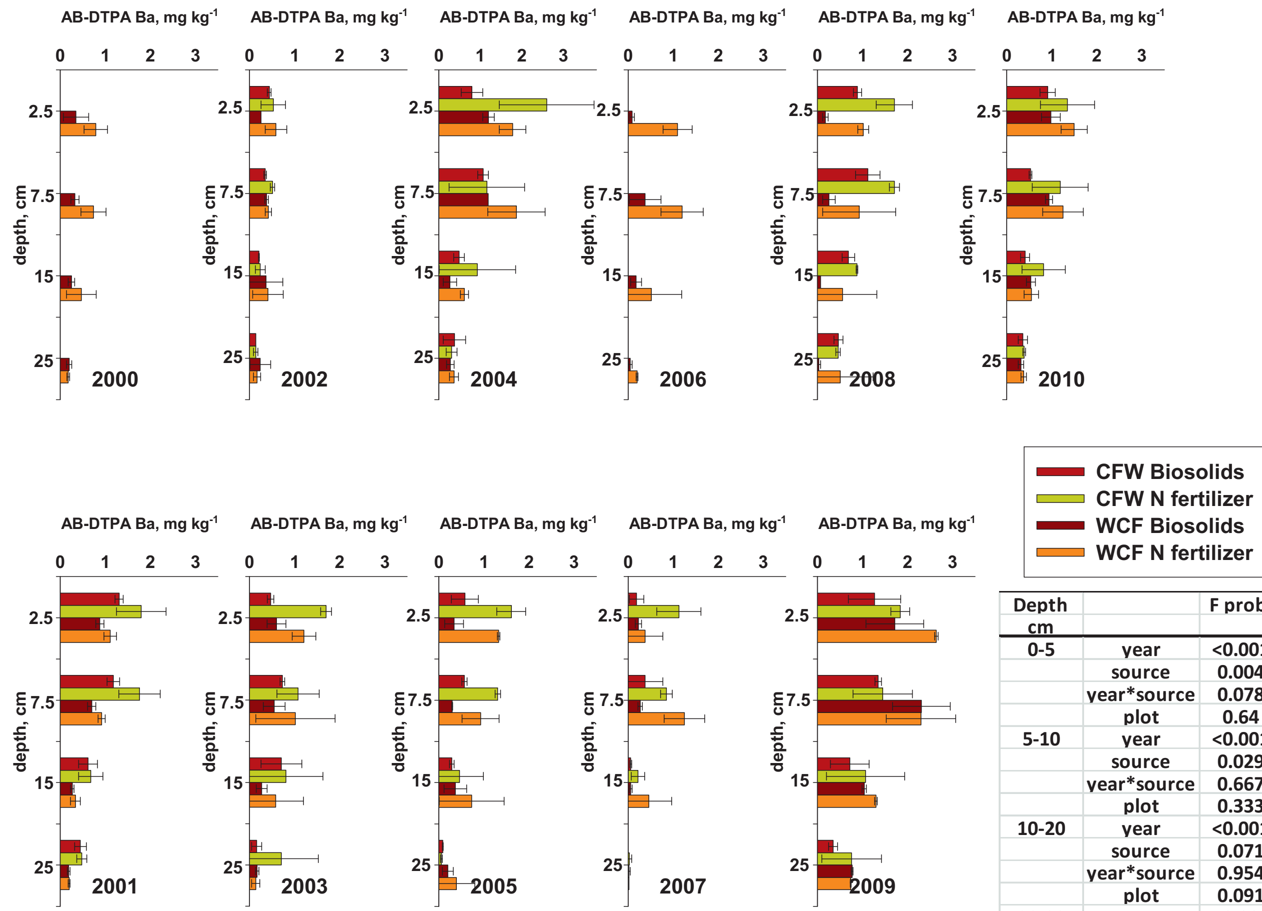
Depth cm		F prob.
0-5	year	<0.001
	source	<0.001
	year*source	0.012
	plot	0.28
5-10	year	<0.001
	source	0.532
	year*source	0.075
	plot	0.059
10-20	year	<0.001
	source	0.631
	year*source	0.988
	plot	0.089
20-30	year	<0.001
	source	0.299
	year*source	0.548
	plot	0.403

Fig. 8. AB-DTPA P for the wheat–corn–fallow and corn–fallow–wheat rotations at the Byers, CO location, 2000–2010. Error bars depict the standard error of the mean.



Depth cm		F prob.
0-5	year	<0.001
	source	0.002
	year*source	0.001
	plot	0.4
5-10	year	0.004
	source	0.034
	year*source	0.043
	plot	0.222
10-20	year	<0.001
	source	0.011
	year*source	0.016
	plot	0.11
20-30	year	<0.001
	source	<0.001
	year*source	0.005
	plot	0.89

Fig. 9. AB-DTPA Zn for the wheat–corn–fallow and corn–fallow–wheat rotations at the Byers, CO location, 2000–2010. Error bars depict the standard error of the mean.



Depth cm		F prob.
0-5	year	<0.001
	source	0.004
	year*source	0.078
	plot	0.64
5-10	year	<0.001
	source	0.029
	year*source	0.667
	plot	0.333
10-20	year	<0.001
	source	0.071
	year*source	0.954
	plot	0.091
20-30	year	<0.001
	source	0.314
	year*source	0.824
	plot	0.28

Fig. 10. AB-DTPA Ba for the wheat–corn–fallow and corn–fallow–wheat rotations at the Byers, CO location, 2000–2010. Error bars depict the standard error of the mean.

Zn, and Ba we sampled to 30 cm and separated the samples into 0–5, 5–10, 10–20, and 20–30 cm depth increments. For soil NO_3–N analyses, we sampled to 180 cm and separated the samples into 0–5, 5–10, 10–20, 20–30, 30–60, 60–90, 90–120, 120–150, and 150–180 cm depth increments.

The soil samples were immediately air-dried and crushed to pass a 2-mm sieve. We determined soil NO_3–N concentrations using a 2 M KCl extraction (Mulvaney, 1996) and soil concentrations of plant-available P, Zn, and Ba in AB-DTPA extracts (Barbarick and Workman, 1987) utilizing inductively coupled plasma-atomic emission spectroscopy (Soltanpour et al., 1996).

For statistical purposes, we analyzed the WF and the WCF rotations as separate experiments. The experimental design for the WF rotation was a split-plot design where year was the main plot and nutrient source (L/E biosolids versus commercial N fertilizer) was the subplot. We used SAS PROC MIXED (SAS, 2010) at the 0.05 probability level to complete the statistical analyses. For the WCF and CFW rotations, we combined the data with the assumption that "plot" would not have a significant effect on the statistical results and we used SAS PROC MIXED (SAS, 2010) at the 0.05 probability level to test for statistical significance. Where a plot effect was found, we did not discuss the statistical results. For the WCF and CFW rotations, corn and wheat yields and grain P, Zn, and Ba were analyzed separately.

3. Results and discussion

3.1. Wheat–fallow rotation

The largest yields were found in 2009 when the greatest amount of precipitation occurred during the wheat reproductive period (Fig. 1; Table 1). A crop failure occurred in 2006 due to the lack of moisture during the wheat reproductive period (Table 1). The nutrient source by year interaction did not affect grain Ba or Zn. Therefore, we accepted Hypothesis 1 and 2 that biosolids would not produce different yields or grain Zn and Ba than N fertilizer for the WF rotation.

Year significantly impacted the soil AB-DTPA P, Zn, and Ba, concentrations at all depths (Figs. 2–4). Nutrient source did not affect AB-DTPA Ba at any depth; however, biosolids produced larger AB-DTPA P at the 20–30 cm depth and Zn in the top 5 cm. The year by nutrient source interaction was significant for AB-DTPA concentrations at several depths. We accepted Hypothesis 3 for the WF rotation AB-DTPA Zn and Ba concentrations since biosolids had no effect on concentrations below 10 cm; we rejected the hypothesis for AB-DTPA P.

The surface AB-DTPA P levels exceeded 7 mg kg^{-1} in all years except 2002, despite the nutrient source. Consequently, all but the 2002 results would be considered as "high" P concentrations and no fertilizer additions would be recommended (Davis and Westfall, 2009). As suggested by Shober and Sims (2003), biosolids additions that follow the agronomic N rates tend to add excess P. The “high” available P levels in the N fertilizer treatment resulted from fertilizer applications before we initiated our study.

According to Follett and Westfall (2004), AB-DTPA Zn concentrations below 1.5 mg kg^{-1} are considered marginal in plant availability. For the 0–5 cm depth, only the 2007 levels for the N fertilizer treatment exceeded 1.5 mg Zn kg^{-1} while biosolids treatment produced soil concentrations greater than 1.5 mg kg^{-1} from 2004 through 2010. Biosolids were an effective Zn fertilizer. Almost every subsoil AB-DTPA Zn concentration was below 1.5 mg kg^{-1}. Barbarick et al. (1997) found similar results in a minimum tillage management system.

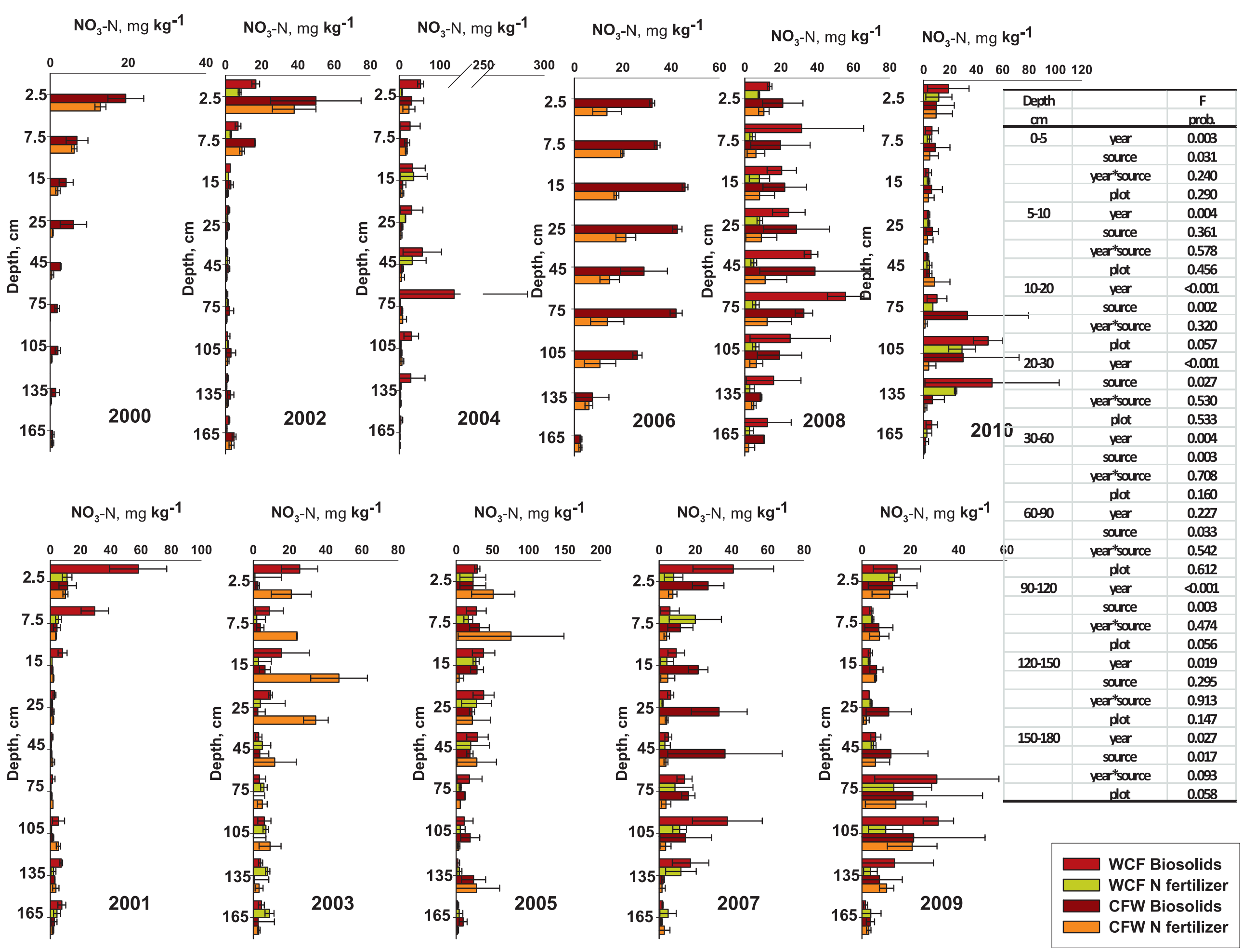
Biosolids application led to significantly larger NO_3–N concentrations in the 30–60 and 60–90 cm depths (Fig. 5). Possibly, these depths reflect the vertical movement of accumulated NO_3–N from the surface since no applications had been made to WF rotations from 2004 through 2010. The year by nutrient source interaction affected NO_3–N concentrations at 0–5 and 10–20 cm (Fig. 5). We reject Hypothesis #4 for WF rotations since biosolids impacted NO_3–N accumulation at several depths. These NO_3–N increases resulted from below average crop yields (Colorado average winter-wheat yields from 2001 to 2010 were about 2 Mg ha^{-1}; USDA NASS Colorado Field Office, 2011) in 2000, 2002, 2005, 2006, and 2008 (Fig. 1) that reduced N removal and also possibly from underestimation of N availability from biosolids applications. Barbarick and Ippolito (2007) based their N equivalency of the biosolids (8 kg N Mg^{-1} per application) on material that had been dried to an average of 74% solids and a total N content of about 2.9%. As shown in Table 2, our Byers site received biosolids that averaged about 21% solids and a total N concentration of about 5.9%. We originally thought that in the no-till system that the NH_4–N in the biosolids would volatilize as the material dried and that lacking incorporation in the soil, N mineralization would be inhibited. Our assumptions apparently were not accurate; thus, a need exists to predict biosolids N availability under agroecosystem management practices similar to those presented in this study. Castillo et al. (2010) provide a technique for estimating N availability from surface application of biosolids in a humid climate. Possibly, this method could be used in dryland agroecosystems.

3.2. Wheat–corn–fallow and corn–fallow–wheat rotations

The 2006 wheat crop was lost because of inadequate moisture during the wheat reproductive stage (Table 1). We experienced corn crop failure in 2002–2006 due to inadequate rainfall during the critical July 16th to August 26th period (Table 1; Nielsen et al., 2010). Biosolids produced lower wheat Ba concentrations (Fig. 6) due to the lowering of AB-DTPA Ba in the top 10 cm of soil (Fig. 10). As Ippolito and Barbarick (2006) reported, biosolids can reduce available soil Ba by forming $BaSO_4$.

Corn grain P and Zn were significantly affected by year and grain P by the year by nutrient source interaction (Fig. 7). The year by nutrient source interaction affected corn yields. Most of the corn grain Ba concentrations were below detection limits.

Biosolids increased AB-DTPA P in the 0–5 cm depth and AB-DTPA Zn at all depths (Figs. 8 and 9) and significant year by nutrient source



Depth cm		F prob.
0-5	year	0.003
	source	0.031
	year*source	0.240
	plot	0.290
5-10	year	0.004
	source	0.361
	year*source	0.578
	plot	0.456
10-20	year	<0.001
	source	0.002
	year*source	0.320
	plot	0.057
20-30	year	<0.001
	source	0.027
	year*source	0.530
	plot	0.533
30-60	year	0.004
	source	0.003
	year*source	0.708
	plot	0.160
60-90	year	0.227
	source	0.033
	year*source	0.542
	plot	0.612
90-120	year	<0.001
	source	0.003
	year*source	0.474
	plot	0.056
120-150	year	0.019
	source	0.295
	year*source	0.913
	plot	0.147
150-180	year	0.027
	source	0.017
	year*source	0.093
	plot	0.058

Fig. 11. Soil NO_3–N for the wheat–corn–fallow and corn–fallow–wheat rotations at the Byers, CO location, 2000–2010. Error bars depict the standard error of the mean.

interactions affected these same parameters. By contrast, biosolids application created lower AB-DTPA Ba in the top 10 cm (Fig. 10) probably due to $BaSO_4$ formation (Ippolito and Barbarick, 2006).

Compared to N fertilizer, biosolids produced larger NO_3–N concentrations at all depths except 5–10 and 120–150 cm (Fig. 11). This accumulation is the result, as discussed earlier, of lack of N removal due to crop failures and underestimation of the biosolids' N availability. We did not find any year by nutrient source interactions.

For the WCF and CFW rotations, we accepted Hypothesis #1 since nutrient source did not affect yields. We accepted Hypothesis #2 for wheat Zn and corn P and Zn, but not for wheat Ba since biosolids actually lowered the grain Ba concentration. We accepted Hypothesis #3 that nutrient source would not affect AB-DTPA Ba and P in the top 10 cm, but rejected the hypothesis for AB-DTPA Zn. Biosolids were actually an effective Zn fertilizer. We rejected the hypothesis that nutrient source would not create different NO_3–N levels throughout the soil profile since biosolids increased the NO_3–N concentrations in most depths.

4. Conclusions

From our study, we learned that surface application of biosolids could replace N fertilizer in a no-till dryland agroecosystem without deleterious effects on wheat or corn yields. Results were mixed regarding movement of P, Zn, and Ba below 10 cm. The biosolids functioned as a Zn fertilizer by improving Zn availability to plants. Lack of N removal by wheat and corn crops and underestimation of N provided by the biosolids led to NO_3–N accumulation.

Several challenges remain. First, can we develop a better estimate of N availability from surface application of biosolids? Secondly, can biosolids act like crop residue and provide greater moisture retention in a no-till management system? Lastly, will surface biosolids application lead to negative effects on runoff-water quality?

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